Journal of Analytical and Applied Pyrolysis xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Analytical and Applied Pyrolysis

journal homepage: www.elsevier.com/locate/jaap

Bio-oil production from Colombian bagasse by fast pyrolysis in a fluidized bed: An experimental study

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ARTICLE INFO

Article history:
Received 12 May 2014
Accepted 13 November 2014
Available online xxx

Keywords:
Fast pyrolysis
Fluidized bed
Bio-oil
Sugarcane bagasse

ABSTRACT

We present experimental results of fast pyrolysis of sugarcane bagasse in a fluidized-bed reactor, in which temperature, biomass feed rate, carrier gas flow, biomass, and effects of inert material particle size on global product distribution were evaluated. For this, changes in the fluid dynamic parameters were made (fluidizing gas flow between 20 and 60 L/min, biomass feed rate between 2.0 and 5.3 kg/h, and inert material particle size between 0.20 and 0.5125 mm). Experimentally, we found that the highest yield of bio-oil was obtained when the reactor was operated at 500 °C, with a carrier gas flow (nitrogen) of 50 L/min, particle size of the inert material and biomass both between 0.600 and 0.425 mm, and biomass feed rate of 2 kg/h. Under these conditions, yields of 72.94% (w/w), 23.28% (w/w), and 3.79% (w/w) for bio-oil, biocarbon, and permanent gases were reached, respectively. Our results show synergic effects between reactivity and fluid dynamics on a fluidized bed, which ensures an efficient, fast pyrolysis process. Therefore, there are two competitive effects related to the particle diameter: first, the yield increases due to heating severity; second, the yield decreases due to entrainment of the smallest particles.

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1. Introduction

Alternative energy sources, such as solar, wind, and those obtained by thermochemical and biochemical transformations of biomass, must compete with traditional oil and coal-derived resources, satisfying the requirements of availability, price, transportation, and environmental and social impact, among others. In this sense, biomass transformation is emerging as an attractive option for Colombia, where it has great potential to meet the demand for sustainable and green energy. Annually, up to 72 million tons of residual biomass are collected, which represents 331 TJ/year of potentially useful energy [1].

Biomass can be transformed into high-energy fuels by biological or thermochemical processes. Biological processes are more selective and require long reaction times in contrast to the thermal processes, which provide multiple and complex products in short reaction times [2]. Among thermochemical processes, combustion, gasification, torrefaction, and pyrolysis are their main exponents.

In pyrolysis processes, biomass is subjected to heating in an inert atmosphere to produce biochar, bio-oil, and permanent gases, whose yields depend on the operating conditions. Pyrolysis at lower heating rates (5–100 °C/min) and temperatures of 400–600 °C is known as slow pyrolysis and is characterized by a high production of biochar (35–40% (w/w)) and low yields of bio-oil (between 25 and 30% (w/w)) [2–5]. In contrast, fast pyrolysis is characterized by high heating rates (>1000 °C/s), temperatures between 300 and 500 °C, and fast cooling of condensable vapors to produce bio-oil as a main product (60–70% (w/w)), 10–15% (w/w) of biochar, and approximately 15–20% (w/w) of permanent gases [2,5–8].

Bio-oil is a viscous, brown liquid, which has a similar high heating value as biomass, approximately 16–19 MJ/kg [2,5,9]. Its chemical composition is complex and depends on the nature of the physicochemical biomass, reaction conditions, and the technology used in the thermal decomposition [5,9]. There are several technological developments for bio-oil production based on fast pyrolysis: pyrolysis in a fluidized bed, free-fall reactors, rotating cone technology, ablative pyrolysis reactors, hot wire (wire mesh), and screw reactor (auger reactor), among others [2,5,8–10].

Fluidized bed and free-fall reactors are the most common technologies reported in the literature and applied in industry (e.g., Dynamotive, EnSyN, METSO/UPM) due to low construction and operating costs in comparison with other alternatives [5,10–12]. Indeed, in 2002, the University of Waterloo in Canada began a project for the construction of a fluidized-bed pyrolyzer to produce

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http://dx.doi.org/10.1016/j.jaap.2014.11.007
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bio-oil with a capacity of 100 ton/day. The reactor began operating in February 2005. However, in 2008, the operation had to be stopped because it was not possible to reach the estimated capacity of the original design [13,14].

Furthermore, in 2006, a second plant with a capacity to produce 200 ton/day began operating [14]. The bio-oil produced was used in a 2500-GT turbine to produce electricity. However, due to variations and limited bio-oil quality, turbines were not used again [14]. Similar experiences have been stopped due to many problems associated with design, scale-up, and start-up. Problems for industrial-scale, bio-oil production are based on the lack of knowledge pertaining to the devolatilization process itself; currently, the decomposition of the biomass kinetics is not clear, and interactions between solid, liquid, and gas phases inside particles have not been well understood. However, the development of this technology does not compete with food security, unlike the transesterification and fermentation processes for producing ethanol and biodiesel, respectively. Additionally, bio-oil can be upgraded, stabilized, and easily incorporated into the existing infrastructure for oil refining; this reduces operating costs compared with the gasification of the same residues [3,15,16]. Also, there is a need to evaluate the interactions between cellulose, hemicellulose, and lignin during pyrolysis and how these kind of macromolecules can affect mass, energy, and momentum transfer processes [17,18].

Many parametric studies of biomass pyrolysis on a fluidized-bed reactor have evaluated the temperature, fluid dynamics, and particle size of bio-oil, biochar, and gas yields. Lira et al. [19] evaluated the effect of temperature on bio-oil, biochar, and gas global yields between 400 and 600 °C, holding the biomass particle size (Amazon tucumã <2 mm) and carrier gas flow ($N_2 = 30 \times 10^{-5}$ Nm^3/s) constant. The optimum temperature to reach the highest bio-oil content was 550 °C, obtaining a 60% (w/w) of yield, from which 20% (w/w) was water. Similar results at 350 °C were reported by Kim et al. [20] for the *Miscanthus sacchariflorus* pyrolysis; the bio-oil yields reached approximately 57.2% (w/w) with a low water content (approximately 25% (w/w)). Additionally, the researchers illustrated that gas residence time is a critical factor for bio-oil quality because gas residence times higher than 1.9 s bring on secondary reactions of vapors. Within this framework, Wang et al. [21] compared the global yields of four biomasses abundant in China (Manchurian ash, China fir, Padauk wood, and rice straw), which were pyrolyzed on a bed reactor at high heating rates. The highest yields were obtained at 500 °C for China fir, Padouk wood, and rice straw and at 550 °C with Manchurian ash. Their biomass feed rate (between 1.4 and 2.6 kg/h) did not have any effect on the bio-oil yield. The highest bio-oil content, which reached up to 55.7%, was obtained from Padouk wood, and 24.6% (w/w) was water. This biomass has the lowest mineral matter content (0.44% (w/w)). In contrast to the 12.2% (w/w) from rice straw, which had a yield of only 33.7% (w/w) with a 53.5% (w/w) for water. Other researchers [22] pyrolyzed sawdust in a fluidized-bed reactor on a bench scale (internal diameter [ID] = 80 mm, height [H] = 300 mm) and evaluated the temperature, particle size, feed rate, and carrier gas flow effects of the global yields. Furthermore, the highest bio-oil yields (approximately 60% (w/w)) and particle sizes greater than 1.3 mm were achieved at 450 °C; at less than 0.3 mm, there is a negative effect on the global product distribution due to a secondary reaction within the particles and sweep through. When the biomass feed rate was varied from 2.5 to 1.5 g/min, the bio-oil was reduced by only 3%. In addition, Heidari et al. [23] performed fast pyrolysis tests with eucalyptus wood on a fluidized-bed reactor. This study is the most complete one we found in the scientific literature related to parametric evaluation (temperature, carrier gas flow, particle size, and biomass feed rate) about the product distribution. Increasing the carrier gas N_2 between 10 and 15 L/min yields bio-oil between 50% (w/w) and 60% (w/w). Related to particle size, they showed that at 1.5 mm it reached the greatest yields, and this is reduced at 10% for higher sizes, due to volatiles secondary reactions inside the particle. The greatest yields are reached at 450 °C (50% (w/w)); meanwhile, the previous one is reduced to 35% (w/w) when the reactor is operated at 600 °C, being that the noncondensable gases yield nearly 50% (w/w). Related to feed rates, there was a parabolic tendency, in which the maximum bio-oil production was achieved at 90 g/h. The feed rates have a direct relationship over the fluidization pattern, product gases flow, solid mixed, heat transfer, volatiles residence time, and secondary reactions. Choi et al. [24] found similar results for sawdust pyrolysis. This research, contrary to previous ones, took into account the condenser temperature for the recovered bio-oil. The bio-oil increases when the cooling temperature reached 10 °C (56% (w/w)) instead of 40% at 40 °C. Lower temperatures promoted bio-oil and biochar lagging, making the product quantification difficult. Similar work related to parametric studies have been reported [25,26].

Most of studies have been performed on bench-scale reactors, in which the product quenching is higher up to 0 °C. Little research have been conducted with fibrous biomass, such as sugarcane bagasse, due to difficulties with the dosification. The inert material particle size of the composition and global yields of permanent gases have not even been explored. Sugarcane bagasse has a high potential of bio-oil production by thermochemical methods due to its high volatile matter content (nearly 80% (w/w)). In addition, these are the most abundant agro-industrial waste in Colombia, having a potential production of 72 million ton/year of biofuels. Additionally, the particle size effect of the inert material needed to enhance the fluid dynamics and heat transfer behavior have not been described.

In this article, temperature, biomass feed rate, carrier gas flow, biomass, and effects of inert material particle size were evaluated based on the global product distribution and composition of permanent gases. Variations were made in the fluid dynamic parameters (e.g., fluidizing gas flow and particle size of the biomass and inert material) to determine the most appropriated operational condition set.

2. Experimental

2.1. Materials and methods

The raw material used was sugarcane bagasse, which is a by-product from the sugar refinery industry in Colombia. This material is produced from the milling step after passing a set of five or six roller mills. Its moisture content reaches approximately 35% (w/w), and its fiber size is 3–5 cm in length on average. To meet feed characteristics for the pyrolysis process, a solar drying step was performed. Then material was ground with a hammer mill of 5 kW power and 3000 rpm, and sieving was performed until a product with uniform particle size (average: 0.5125 and 0.075 mm) and moisture content below 10% (w/w) was obtained. Once the biomass was prepared, physicochemical characterization was performed (e.g., elemental, proximate analysis and lignocellulosic material content).

2.2. Raw material characterization

Biomass particles with an average size less than 0.25 mm (size 60 mesh) are required for analytical procedures. To establish the biomass elemental composition (CNHOS), an adjustment of the ASTM D5373 standard was used by applying an EXETER CE 490 elemental analyzer. The ultimate analysis was performed by adapting the ASTM protocols established for coal but applying them to biomass. For determination of lignocellulosic material content,

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Table 1
Physico-chemical biomass composition.

Lignocellulosic biomass composition, % (w/w)		
Cellulose	43.55	NREL/TP-510-42618
Hemicellulose	32.99	NREL/TP-510-42618
Lignin	21.76	NREL/TP-510-42618
Elemental analysis, % (w/w)		
%C	46.6	ASTM D 4239
%H	5.92	ASTM D 4239
%N	0.14	ASTM D 4239
%S	0.09	ASTM D 4239
%O	43.35	By difference
Proximate analysis, % (w/w)		
Ash	3.90	ASTM D 3172
Moisture	5.25	ASTM D 3173
Fixed carbon	8.30	ASTM D 3175
Volatiles	82.55	ASTM D 3174
High heating value, cal/g	4040	ASTM D 5865
Bulk density, kg/m^3	54.9	–

methodologies developed by NREL/TP were chosen [27]. Results of the physicochemical characterization are summarized in Table 1.

As shown in Table 1, both biomass volatile and hemicellulosic material contents are high, which indicates a high potential to produce bio-oil by this feedstock. Also, its mineral material content is low; therefore, no strong catalytic effect promoting formation of biochar and gas is expected. The biomass proximate analyses were performed by the ASTM D 3172-3175 applied for coal. Importantly, the moisture in the reported proximate analyses was 5.25% (w/w), which is lower than raw biomass employed in experimental tests (10% (w/w)). This is due to the mass loss by water evaporation in the milling process caused by frictional heating (size for analysis <0.25 mm).

2.3. Product characterization

The bio-oil was recovered directly in a cooling unit (condenser) designed by the researcher team. On average, it is able to reach temperatures as low as −26 °C, and currently it is in patent registry. After it was collected, it was weighed to determine the global yield. The bio-oil moisture was measured using the ASTM E 203 method. A Karl Fischer Titrator (Metrohm 787 KF Titrino) was used, and HYDRANAL composite 5K (Riedel de Haen) and HYDRANAL working medium K (Riedel de Haen) were used as the titration reagent and titration solvent, respectively. The deviations of the above analyses were less than 1%. The sample weight to avoid interface between aldehydes and the titrator was less than 20 mg of bio-oil. The biocarbon was collected in the cyclone, and inside of the reactor, it was weighed to find out the biocarbon yield. Biocarbon samples recovered were analyzed by the ASTM D 5865 used for coal.

The gas product yields were measured by the differences between the biocarbon and bio-oil yields, therefore measuring the experimental difficulties from the outer gases. The gas sampling procedure was performed using a cleaning train consisting of a particle filter and bubbling and impinger system with silica gel. Varian Model CP3800 gas chromatography equipment was used with StarCromatography Workstation software. Two packed columns installed in series (Mol sieve and Hyesep both 3 m and with an internal diameter of 2.5 mm) were used with BackFlush-Bypass configuration. The analyses were performed at isothermal condition at 40 °C for 20 min with a TCD detector set at a temperature of 170 °C.

2.4. Experimental equipment description

The pyrolysis process was performed in a bubbling fluidized-bed reactor (Fig. 1). An inert particle bed (20 cm height) homogenized the heat distribution in the reactor. Also, biomass and gas carrier flows were adjusted according to experiment goals. The experimental design is summarized in Table 2.

The stainless steel reactor has an internal diameter and height of 10 cm and 50 cm, respectively, at the reaction zone (bed) and 14 cm in diameter and a height of 100 cm in the free zone (freeboard). The unit is isolated by a ceramic material. Power is supplied to the reactor through a set of three electric heaters (1500 W each), located along the reactor. Temperature control was adjusted using a PID temperature controller and was monitored using three K-type thermocouples.

2.5. Experimental conditions

The reactor was charged initially with 2 kg inert silica sand (diameters: 0.200, 0.3375, and 0.5125 mm) to help the fluidization and heating. Nitrogen was used as a carrier gas with flows from 20 L/m to 60 L/m. Initially, all nitrogen was purged from the system before each test, and the oxygen was verified by gas chromatography. Once the reactor reached the set-up temperature, the feed screw was turned on with the purpose of dosifying the biomass continuously with flows from 2.0 to 5.3 kg/h. Table 2 illustrates how the experiment is run.

Runs 1 and 2 were conducted to investigate the pyrolysis temperature effect, which ranged from 500 to 550 °C. In runs 3–6, the biomass feed rates were performed to 2, 3, and 5.3 kg/h, respectively. Sugarcane bagasse particle size in runs 1 and 7 were changed from 0.512 mm and 0.075 mm. Also the effect of the inert particle size was studied for the distribution of global products. For this purpose, runs 8 and 9 were performed. The 10–13 runs were performed to determine the carrier gas flow effect for the product pyrolysis. Runs 14–16 were performed to compare the global products of the four biomass types using the experimental conditions of run 1. Each test was performed twice, and the reported results are averaged values.

3. Results and discussion

In each experimental trial, the mass balance was checked. The bio-oil yield was determined by weighing the collected liquid in the condenser (−26 °C) at the end of the experimental test. Likewise, it is preceded by biochar, which is recovered in the cyclone and inside the reactor (fraction). The product gas global yield was measured by differences due to difficulties in experimental measures of permanent gas flow.

3.1. Effect of temperature on process performance

Biomass fast pyrolysis tests at 500 and 550 °C were performed with their respective duplicate. These were performed with biomass particle sizes (D_p) with an average of 0.5125 mm, fluidizing gas (N_2 at 50 L/min), biomass feed rate (2 kg/h), inner particle size (silica sand in diameter average 0.512 mm), and condenser temperature fixed at −26 °C. We observed that, as the process reached approximately 550 °C, the yield of both bio-oil and biochar decreased; this was a logical result because secondary reactions of decomposition of volatile that are favored with the increase in temperature [28–30]. An increase in permanent gases is shown in Fig. 2. The results are consistent with the experimental observations reported by Bridgwater [2] and elsewhere [19,22,25].

Regarding the permanent gases, a greater participation of CO in the flue gas was observed as the process temperature increased (Fig. 3).

Temperatures greater than 500 °C, secondary reactions of volatiles, cracking and incipient gasification of both homogeneous and heterogeneous phases are favored. In addition, the reactions

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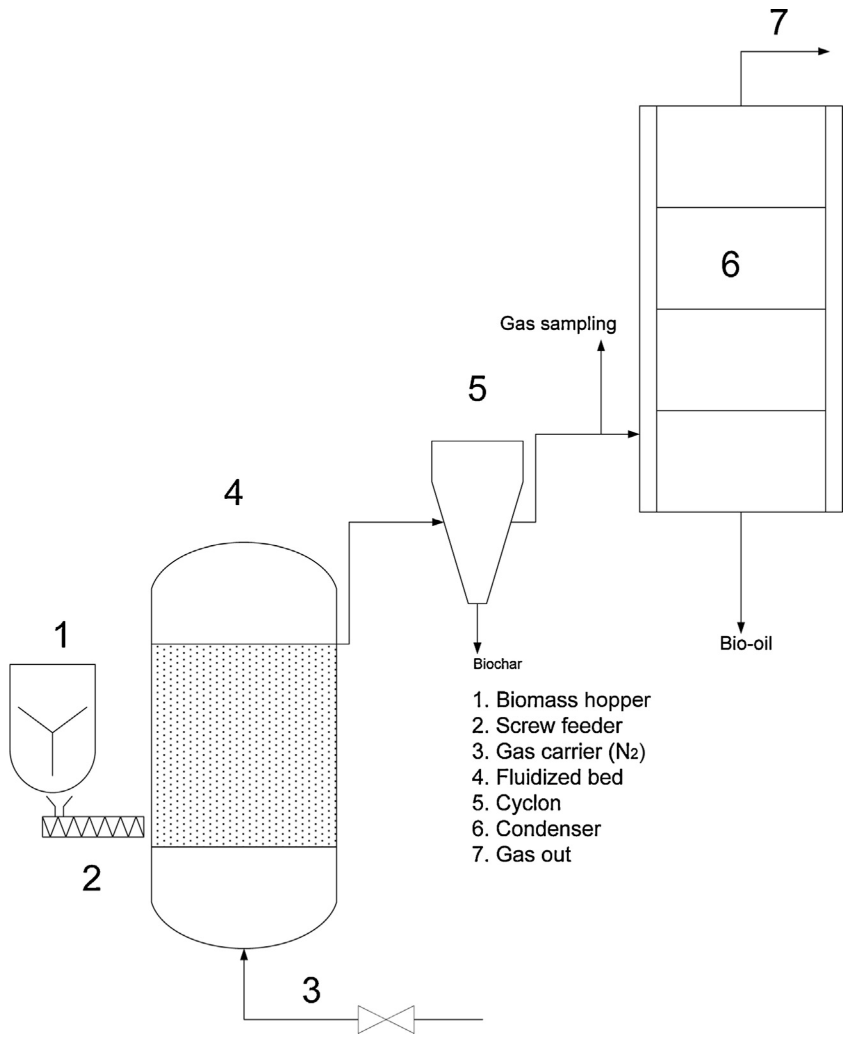

Fig. 1. General scheme of experimental equipment.

of biochar with water vapor shows a similar trend, leading to increased production of carbon monoxide, which is consistent with other reported experimental results [25,31]. Furthermore, it is possible that incipient detachment of alkyl ether functional groups from the lignin structure occurs, which usually decompose in the homogeneous phase, forming carbon monoxide. However, notably, differences in concentration are given in a narrow range; the CO levels up from 2% (v/v) to 6% (v/v) due to the fragmentation reactions of the carbonyl group. Methane, formaldehyde, formic acid, acetic acid, methanol, and hydrogen are released, and biochar is being

Table 2
Experimental conditions.

Parameter	Experimental assay number							
	R1	R2	R3	R4	R5	R6	R7	R8
Biomass type	SCB	SCB	SCB	SCB	SCB	SCB	SCB	SCB
Temperature (°C)	500	550	500	500	500	500	500	500
Biomass particle size (mm)	0.512	0.512	0.512	0.512	0.512	0.512	<0.075	0.512
Gas flow rate (l/min)	50	50	50	50	50	50	50	50
Feed rate (kg/h)	2.0	2.0	2.0	3.0	3.0	5.3	2.0	2.0
Inert particle size (mm)	0.512	0.512	0.512	0.512	0.512	0.512	0.5125	0.200

Parameter	Experimental assay number							
	R9	R10	R11	R12	R13	R14	R15	R16
Biomass type	SCB	SCB	SCB	SCB	SCB	S	PR	BR
Temperature (°C)	500	500	500	500	500	500	500	500
Biomass particle size (mm)	0.512	0.512	0.512	0.512	0.512	0.512	0.512	0.512
Gas flow rate (l/min)	50	20	30	40	60	50	50	50
Feed rate (kg/h)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Inert particle size (mm)	0.3375	0.512	0.512	0.512	0.512	0.5125	0.5125	0.5125

Note: SCB, sugarcane bagasse; S, sawdust; PR, palm rachis; BR, banana rachis.

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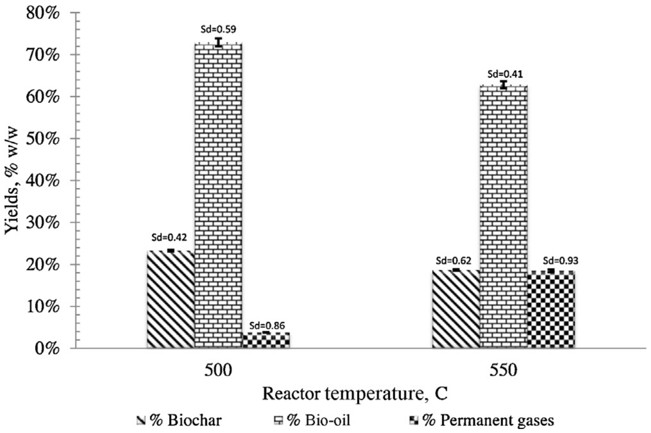

Fig. 2. Variation of the pyrolysis products with reactor temperature.

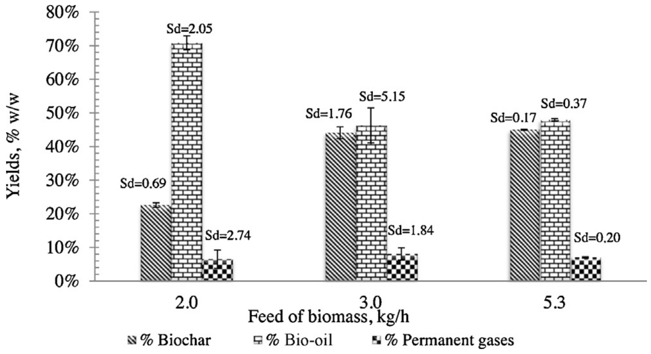

Fig. 4. Variation of pyrolysis products with biomass feed rate.

formed. The primary products are beginning to react with each other before they can escape the reaction zone [32]. The methane slightly increases from 0.45% (v/v) to 0.72% (v/v), which can be explained by demethylation reactions of the lignin [33] or by a methanation reaction between H_2, CO, and CO_2 [34,35].

3.2. Biomass feed rate effect on process performance.

Biomass fast pyrolysis tests at 500 °C with their respective duplicate were performed. These were performed with biomass particle sizes 30-mesh (particle diameter D_p on average 0.512 mm), fluidizing gas (N_2 at 50 L/min), biomass feed rate (2, 3, and 5.3 kg/h), inner particle size (silica sand on average 0.512 mm), and condenser temperature set-up at −26 °C. Increased biomass feed rate is equivalent to approximately the amount of solids charged to the reactor level up; therefore, it is expected that the heating rate of the particles level off, and the solid volumetric fraction inside the reactor grows because this increases the superficial solid areas, promoting heterogeneous secondary reactions. That is why with the same power supplied to the reactor, a greater amount of biomass must be heated, obtaining each time a transition from a fast pyrolysis process to another slow pyrolysis process, in which the dehydration instead of depolymerization reactions are promoted (Fig. 4).

As the biomass feed rate increases, the bio-oil falls from 70.88% (w/w) to 47.94% (w/w) (inasmuch as a great biomass feed rate produces greater biochar content) and lightly increases the production of permanent gases [26]. For higher flows than 2 kg/h, competitive effects occur, which disturb the fluid dynamics (increases of solid volumetric fraction) and reduce the energy transfer severity (decreases radiation between solid and particles), promoting carbonization and dehydration reactions against bio-oil production. An increase of the residence time of particles induces water production; this allows for incipient gasification reactions [31].

Water vapor accumulation inside the reactor encourages secondary reactions between biochar and carbon dioxide. Hence, it is likely that, at the process temperature, the water vapor reacts with biochar to form carbon monoxide and hydrogen, which corresponds to an endothermic gasification reaction. Although the gasification reaction does not have a high degree of conversion at 500 °C, at which the heterogeneous reaction is feasible [31], the progress of secondary reactions between the biochar and the volatiles is facilitated, producing gas proportions shown below in Fig. 5.

It is not easy to explain the trend of gas behavior (Fig. 5) because the process is influenced by a wide variety of physical (heat transfer, mass transfer, agglomeration of solids, hydrodynamics of the bed, changes in porosity) and chemical phenomena. Also, for competitive reactions, there are both homogeneous and heterogeneous phases. The fluidizing gas medium has an effect on the composition of permanent gases, as reported by. It is forward the relationship between feed rates and the mass of permanent gases released within the reactor. As permanent gases increase inside the reactor, the partial pressure of the inert gas (N_2) decreases; therefore, the CO_2, CO, and hydrocarbons with condensable vapors could be important as hot zones inside the reactor.

3.3. Effect of carrier gas flow on the global process yield

Biomass was pyrolyzed on a fluidized-bed reactor at 500 °C. The feed rate of biomass was 2 kg/h, with a particle diameter on average 0.5125 mm, using 2 kg of silica sand with a particle diameter

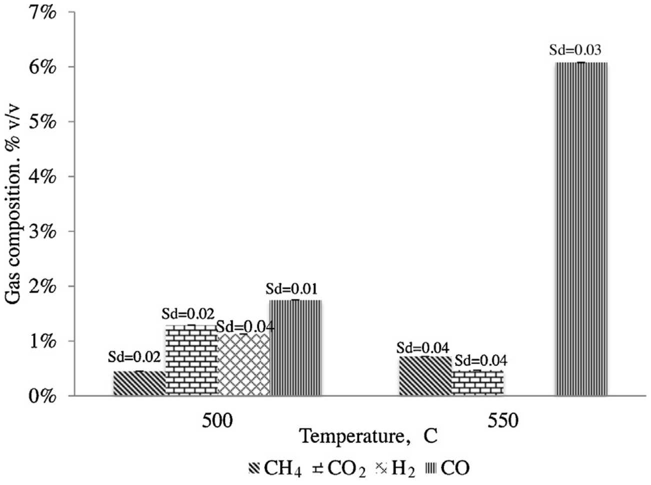

Fig. 3. Temperature effect on gas composition.

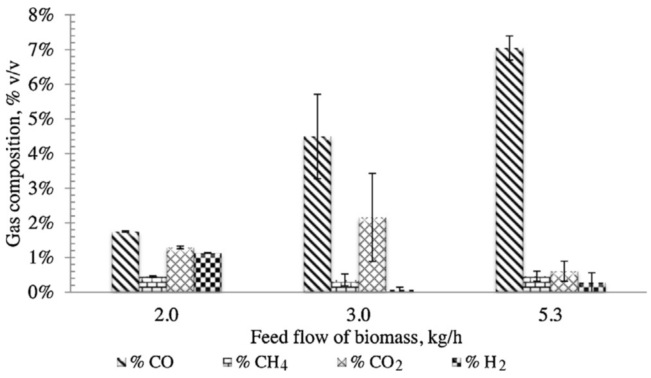

Fig. 5. Variation of gas composition with biomass feed rate.

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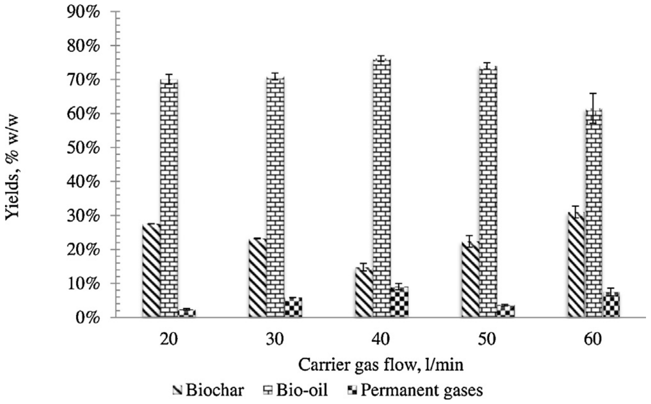

Fig. 6. Variation of pyrolysis products with carrier gas flow.

on average 0.5125 mm, holding constant temperature of the condenser at $-26\,^{\circ}$C, and varying the carrier gas flow at 20, 30, 40, 50, and 60 L/min. Based on the experimental results (Fig. 6), between 40 and 50 L/min, there is a transition zone, in which the residence times of volatiles and biomass are suitable, reaching a maximum yield of bio-oil (68.45%).

At 60 L/min, the residence time of solids and volatile is low (due to the solid sweep without reaction); hence, low biomass conversion is achieved with higher production of biochar (Fig. 6). Between 20 and 30 L/min, the residence times of solids and volatiles are higher; this is because the product gases in solid thermal decomposition are able to produce secondary reactions [36] and increase formation of permanent gases, such as CO and CO_2 (Fig. 7).

For 30 L/min, there is a higher consumption of biocarbon inasmuch as the particles inside the bed are more expanded and energy/volume that gets to the particles is higher (higher heating rate).

Notably, there is a competitive effect between the residence times of volatiles and solids. As the residence times of solids increase, devolatilization increases; contrary to the high residence times of the volatiles, decomposition reactions that decrease bio-oil are promoted.

Between carrier gas flows of 40 and 50 L/min, there is a transition zone in which both the residence times of biomass and volatiles level off, reaching a maximum yield of bio-oil at 50 L/min. Nevertheless, this high yield does not retrieve the low heating values of both bio-oil and biocarbon (Fig. 8), rather the slight increment of the heating value of permanent gases.

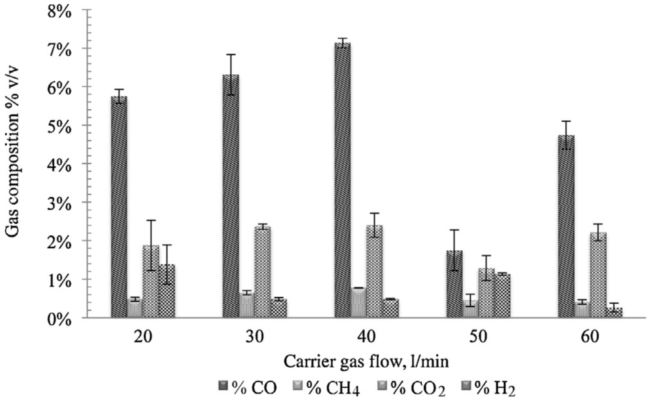

Fig. 7. Composition of permanent gases at different carrier gas flows.

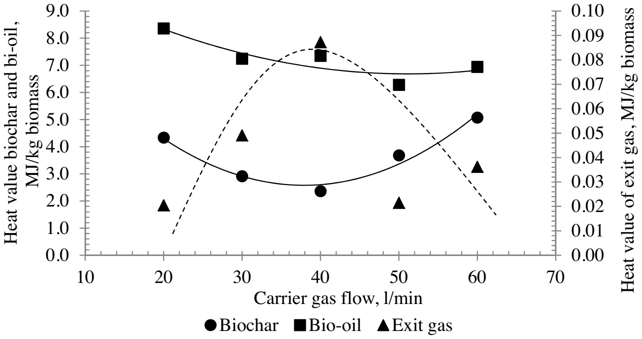

Fig. 8. High heating value of the pyrolysis product expressed in energy unit per kilogram of raw material (biomass) at different carrier gas flows.

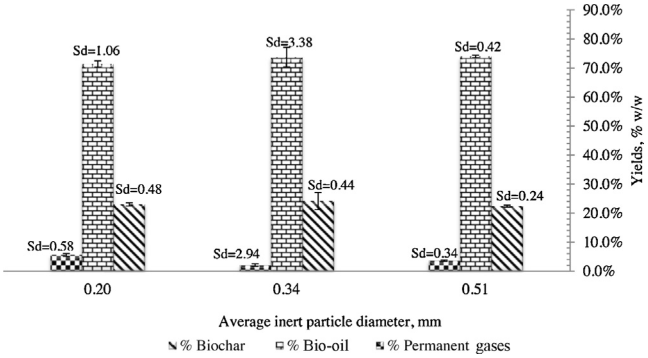

Fig. 9. Variation of pyrolysis products with different silica sizes.

3.4. Effect of silica sand particle size on process yield

The effect of the silica particle size on the overall yields of bio-oil, biochar, and gas was evaluated using particle sizes of 0.5125 mm ($0.600\,\text{mm} < D_p < 0.425\,\text{mm}$), 0.3375 mm ($0.425\,\text{mm} < D_p < 0.250\,\text{mm}$), and 0.200 mm ($0.250\,\text{mm} < D_p < 0.150\,\text{mm}$). All tests were performed at a carrier gas flow of 50 L/min. The biomass particle size was on average 0.5125 mm, and the feeds rate was fixed in 2 kg/h. In Fig. 9, the effect of silica sand particle diameter on overall yields is shown below.

There are no strong effects on biochar, permanent gases, and bio-oil yields. However, the high heating value per kilogram of biomass has a maximum (Fig. 10) for average particle size (0.3375). This unusual behavior has not been reported in the literature.

The experimental results were duplicated for reproducibility. One possible explanation for this phenomenon is shown in Fig. 11. Bio-oil yield is affected by both gas solid contact time and the

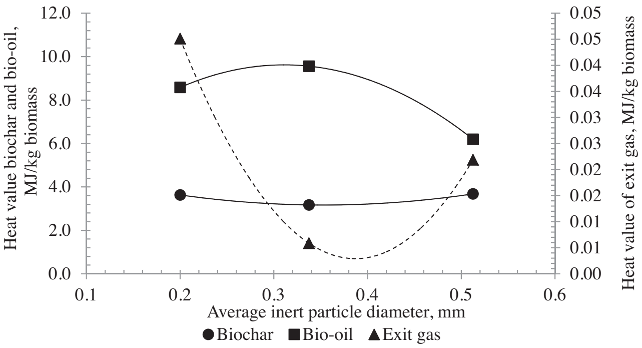

Fig. 10. High heating value of the pyrolysis product expressed in energy unit per kilogram of raw material (biomass) at different inert material (silica) sizes.

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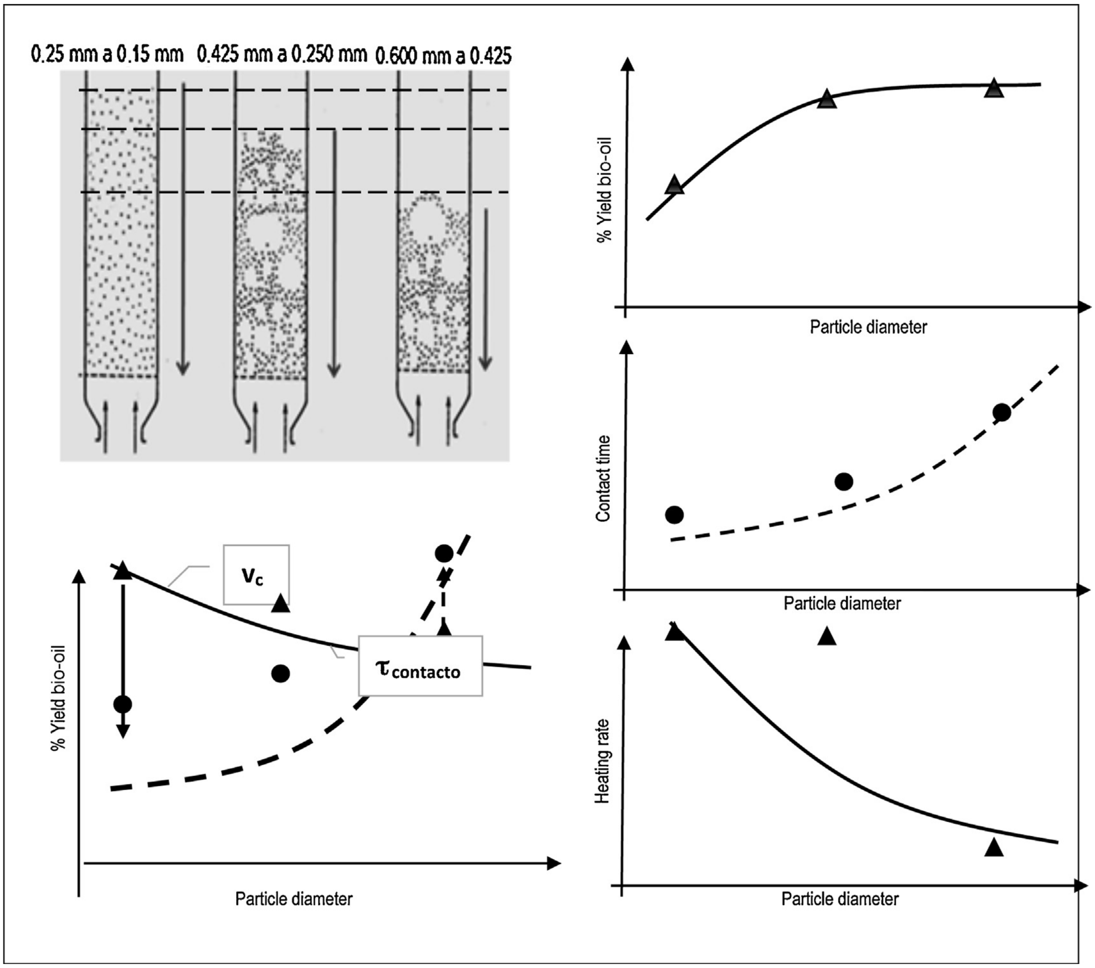

Fig. 11. Fluidization pattern for 3 sizes of silica. Carrier gas flow (50 L/min) and particle diameter (0.513 mm, 0.338 mm, and 0.200 mm).

heating rate: the global bio-oil yield increases as contact time decreases; the opposite occurs with the heating rate, in which the yield levels off.

Based on laboratory experiments, it was possible to vary the heating rate and residence time by modifying the fineness of the inert material. It was observed that the heating rate falls as the particle size increases (Fig. 11). The residence time also levels off with the increase in the particle size of silica sand.

There are two competing effects with respect to the particle diameter: first, the yield increases with the increase of particle size; second, the yield levels off to the extent that size increases (Fig. 11). From the above arguments, it can be inferred that, despite achieving higher heating rates and increased devolatilization with a particle size of 0.200 mm, the bio-oil yield is not optimal (close to 71.40% (w/w)) because the decomposition of generated volatiles is also important. From this perspective, for a particle size of 0.5125 mm, the heating rate is not as high as for other sizes. However, the contact time of the volatiles with silica sand is low, such that no decomposition reactions are favored; thus, the bio-oil yield is favored. Concerning the average particle size, there is a combined effect of both heating rate and the contact time of the volatiles, which does not promote the bio-oil yield. We observed a behavior in which carbon monoxide and other permanent gases slightly increase as the particles size increases (Fig. 12).

The effect of the diameter of the inert material on the production of permanent gases supports the hypothesis that greater silica sand diameter decreases the activity of the secondary reactions (Fig. 12). The bio-oil has less heating value, probably because it possesses a higher proportion of oxygen when inert particles of larger diameter are used.

3.5. *Effect of biomass particle size on the process yield*

Concerning the effect of biomass particle size on bio-oil and biochar yield, experimental tests were performed, holding the constant process temperature at 500 °C, biomass feed rate of 2 kg/h, and carrier gas flow at 50 L/min, varying the grain size (particle groups: diameter smaller than 0.075 mm and on average 0.5125 mm). With

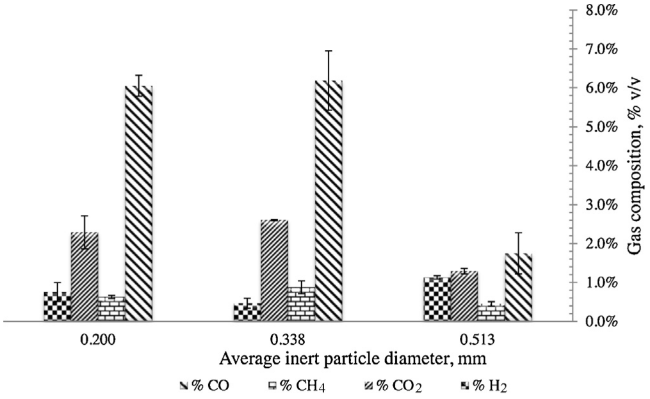

Fig. 12. Effect of the particle size of inert material on the composition of permanent gases.

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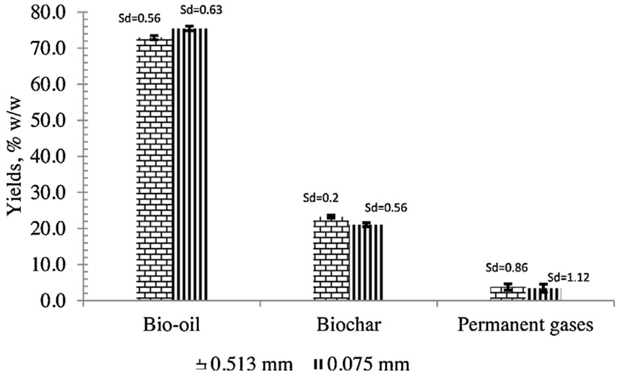

Fig. 13. Effect of biomass particle size on pyrolysis products.

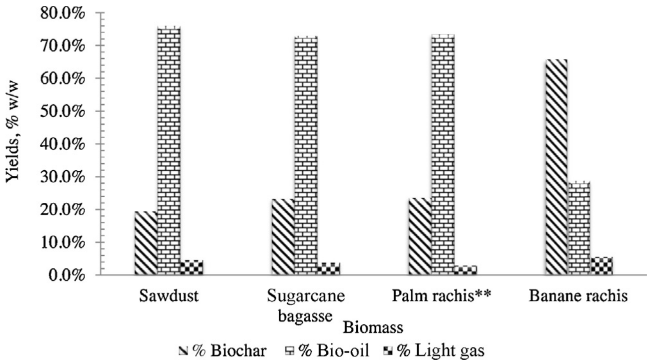

Fig. 15. Yields obtained by different types of biomass.

small particle sizes, high heating rates are reached compared with slow heating with a bigger particle (Fig. 13).

When the sugarcane bagasse particle size was increased to 0.5125 mm, the bio-oil yield leveled off close to 3.4% (w/w) until 72.9% (w/w). Meanwhile, the biocarbon yield increased to 9.6% (w/w), and the quantity of permanent gases was unchanged. This is related to the particle heating rate: a big particle is heated slowly, which is why less volatile material is released and, at the same time, produces more biocarbon. With a biomass particle size of 0.075 mm, the bio-oil increases and biocarbon decreases, both due to overheating by small particles [24,25].

As the particle size increases, biochar and production of permanent gases increase (Fig. 14), which is an expected result consistent with studies reported in the literature [37].

3.6. Yield comparison with different biomasses

During the extensive experimental program, tests were performed with different raw materials: pine sawdust, sugarcane bagasse, and palm and banana rachis (Table 2). These biomasses were subjected to fast pyrolysis under the experimental conditions reported in Table 2.

In Fig. 15, these results were obtained by four different biomasses submitted to fast pyrolysis under operational conditions used in run 1 (Table 2). A better performance was obtained when both sawdust and bagasse were pyrolyzed. This is in agreement with the composition of these raw materials, which are basically soft biomass with a low amount of mineral material, which decreases the possibility of catalysis of secondary reactions affecting productive performances. Even though they produced high yields, both sawdust and palm rachis are not promising for use as biofuels due to the low amount of this agro-industrial waste. Furthermore, with the material processing, it is expensive and requires high energy consumption.

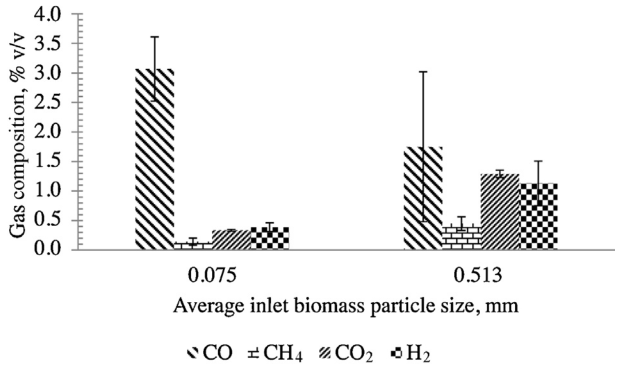

Fig. 14. Effect of biomass particle size over permanent gases compositions.

4. Conclusions

Fluidized-bed technology is suitable for pyrolysis of different kinds of biomass. This allows the production of bio-oil from agro-industrial residues, such as sugarcane bagasse, with yields of approximately 70%. Our data support that the heating rate is the main parameter to achieve a high yield. The temperature process, particle size, and biomass feed rate define the particle heating rate and solid residence time, which have more effect on the bio-oil yield.

Also, the feed rate has little effect on the compositions of permanent gases; however, it is a complex phenomenon, and it is difficult to explain the variation of the competition of permanent gases as the feed rate changes. These changes have been quite difficult to understand due to several combined phenomena (e.g., feed rate affects the heating rate, resident time of solids and gases, and the contact time between solid and gases).

A synergic behavior exists between reactivity and fluid dynamics on a fluidized bed that make the fast pyrolysis process efficient. Therefore, one should ensure that the operational parameters promote the devolatilization and, at the same time, holding the fluidized bed also must be ensured. Therefore, there are two competitive effects related to the particle diameter: first, the yield increases due to heating severity; second, the yield decreases due to entrainment of the smallest particles.

Acknowledgments

The authors thank the Laboratory of Chemical Analysis of Coals from National University – Colombia for biomass and biochar characterization, COLCIENCIAS and National University – Colombia for the financial support of doctoral studies for Jorge Iván Montoya A. We also want to thank ECOPETROL for the financial support and accomplishments with this research.

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